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DEBRIS CONTROL AT HYDRAULIC STRUCTURES

CONTRACT MODIFICATION:

MANAGEMENT OF WOODY DEBRIS IN
NATURAL CHANNELS AND AT
HYDRAULIC STRUCTURES

by

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UNITS OF MEASUREMENT

Units of measurement used in this report can be converted as follows:

To convert	To	Multiply by
inches (in)	millimetres (mm)	25.4
feet (ft)	meters (m)	0.305
yards (yd)	meters (m)	0.914
miles (miles)	kilometres (km)	1.61
feet per second (ft/sec)	meters per second (m/sec)	0.305
square feet (sq. ft)	square meters (m^2)	0.093
square yards (sq. yd)	square meters (m^2)	0.836
square miles (sq. miles)	square kilometres (km^2)	2.59
acres (acre)	hectares (ha)	0.405
acres (acre)	square miles (m^2)	4050
cubic feet (cu ft)	cubic meters (m^3)	0.0283
cubic yards (cu yd)	cubic meters (m^3)	0.765
cubic feet per second (cfs)	cubic meters per second (cms)	0.0283
pounds (lb) mass	kilograms (kg)	0.453
tons (ton) mass	kilograms (kg)	907
pounds force (lbf)	newtons (N)	4.45
kilogram force (kgf)	newtons (N)	9.81
acre-feet (acre-ft)	cubic metres (m^3)	1230

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1 INTRODUCTION

1.1 Work Unit Outline

This report contains a compilation of results and conclusions from four research projects assessing the impact of Large Woody Debris (LWD) on channel geomorphology in the Yazoo Basin, Northern Mississippi, and the impact and control of LWD at hydraulic structures. The long-term aim of this research is an improved understanding of the basin-wide impact of LWD dynamics in unstable and stable channel environments, the development of coherent basin-wide debris management strategies for erosion control, habitat enhancement, and maintenance/design procedures for DEC and run-of-river structures, based upon sound engineering-geomorphic analyses. The research was initiated through the following work unit :

PROGRAM : 331 - Flood Control Structures

WORK UNIT # 32873 PRIORITY 4

WORK UNIT TITLE : Debris Control at Hydraulic Structures

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PROBLEM

During floods, debris build-up at hydraulic structures spanning streams can be a serious problem. While the problems of floating debris in reservoirs have been more or less solved, debris which piles against run-of-the-river structures with no intervening pool to catch and slow down the load causes serious operational problems and is occasionally a threat to structural integrity.

OBJECTIVE

Develop methods of handling floating debris loads in streams which eliminate threats to the operational and structural integrity of in-stream hydraulic structures.

DESCRIPTION

Quantify and classify problems Districts have had with floating debris. Examine literature for any previous mention of problems and solutions. Develop methods of alleviating most frequently caused problems. Use physical model studies, if necessary. Methods for minimizing debris problems at bridges are included as a product of this work.

BENEFIT

Reduce costs of managing floating debris at run-of-the-river hydraulic structures.

1.2 The Geomorphological Impact of LWD

This aspect of debris control has been assessed in the following reports: Wallerstein & Thorne (1995 and 1996) and Cheesman (1995).

There has been increasing interest in the role of vegetation in fluvial geomorphology in recent years because it has been recognised that river dynamics cannot be fully understood without taking into account the impact that vegetation has upon bank stability, hydraulic characteristics, and riverine habitat.

As a consequence the study of in-channel Large Woody Debris (LWD) or Coarse Woody Debris (CWD) as it is sometimes referred to (defined as: trees, branches and other larger organic matter, operationally defined as material with a length greater than 1 metre) and its accumulation as jams or dams and impact upon the channel environment has become a topic receiving increasing research interest over the past 5 to 10 years.

In an initial review of relevant literature undertaken (Wallerstein 1994) it was established that a large proportion of the research performed to date has been carried out in upland areas, and in stable, gravel bed rivers such as in the Pacific North West (Hogan et al., 1995; Fetherston et al., 1995) to determine the impact of LWD on salmon habitat and migration, and in relation to logging operations and forest management. Relatively little is known about the impact of LWD in sand bed, or unstable rivers. Much of the existing knowledge is fairly qualitative and observational in nature and there has been little emphasis on determining the key variables at play in LWD dynamics, and the modes of their interaction. Most studies have also been undertaken in isolated reaches, rather than covering watershed-wide processes, although there are one or two notable exceptions (see Gregory et al., 1993). LWD management is, therefore, often conducted on an *ad hoc* basis due to an incomplete understanding of debris dynamics.

The aim of this research effort has, therefore, been to asses the watershed wide impact of LWD over a wide range of channel sizes but in unstable, rapidly evolving rivers with sand, clay and loess bed and banks. The research in this project has been centered on streams in the DEC (Demonstration Erosion Control) watersheds draining the Bluff Line hills of North Mississippi, which are known to be evolving rapidly in response to complex response in the fluvial system following catchment land-use changes and past engineering interventions.

The specific aims of this research were:

1) To collect a large, meaningful data set concerning the reach scale and basin-wide influences of LWD on channel morphology in a different type of channel environment to that which has been studied so far, namely unstable, rapidly evolving sand-bed rivers.

2) To asses whether there are preferential sites of debris input and accumulation within the channel environment and the stability of debris jams in term of there longevity in a particular reach.

3) To investigate how effectively debris jams inhibit or promote bed scour, sediment transport and storage in order to determine whether they are net stabilising or destabilising elements in the system.

4) To develop a set of guidelines for in-channel LWD management that can be used by engineers and river managers as an aid to assessment, design and maintenance of stable channels, and production of guidelines for LWD management technologies at run-of-river structures.

Data from the US Army Corps of Engineers DEC survey program, conducted in May 1994 and May 1995 has been used to locate significant debris jams, with respect to planform and long profile data on twenty three river reaches in the Yazoo Basin. The reaches surveyed are between 4,000 and 12,000 feet long and range in upstream basin area from between 3.5 to 150 square miles. A comprehensive understanding of debris dynamics can be attained from surveying these channels because reaches fall into several categories including, stable/unstable reaches, straight/meandering reaches and reaches which have either a predominantly agricultural or wooded riparian zone. The debris jams in each reach have been surveyed in detail to determine the mechanisms and locations of debris input, jam impact upon channel morphology, sediment routing, and jam stability over time.

The geomorphological characteristics of jams in each reach have been analysed and plotted against independent catchment variables, including drainage basin area, stream power and average channel top width to determine whether the geomorphological effects of LWD have a coherent and predictable, spatial relationship. Debris jam sediment budgets have also been calculated and related to spatial parameters to determine whether the net impact of debris jams is sediment retention or sediment scour and mobilisation. An understanding of this factor is important as it indicates whether LWD is a net stabilising or destabilising agent in sand-bed rivers.

This report presents a state-of-the-art review of literature concerning the geomorphological and hydraulic impact of LWD, a summary of the survey results obtained to date, and a summary of the LWD Management Program developed to predict the geomorphological impact of in-channel LWD. An overview is also given of the demonstration GIS system (Cheesman, 1995) which supplies data to the management program for a typical, representative DEC watershed.

1.3 Debris at Run of River Structures

Debris problems and control measures at run of river structures has been assessed in detail in Wallerstein et al. (1996).

Floating debris can create severe problems for a variety of structures and water-based activities. Debris can destroy the propellers of recreational and commercial boats and cause damage to boat hulls. Navigation lock operation can be impaired by debris caught on a gate sill. Floating debris has the greatest economic effect on users of large quantities of water such as hydro-electric and thermal-electric generating plants and municipal water systems. On occasion dam gates can become stuck partly open by debris intrusion and severe downstream bed scour may occur. Floating debris can also damage the upstream slopes of dams through wave action which hammers debris against the dam wall and other structures.

In order to develop improved and more cost-effective debris control systems it would be beneficial to have a sound understanding of debris dynamics within the relevant catchment area, upstream of that structure. Basin-wide studies can help engineers to make more informed decisions on debris management and to design better measures for counteracting debris damage and disruption at structures. However, even with the most efficient catchment management measures, some debris will always arrive at structures and plant operators must, therefore employ design features or install devices to prevent floating debris from entering and damaging turbines, valves, gates, and pumps.

Debris control and exclusion systems involve considerable capital cost, and require difficult and expensive maintenance procedures. They may also impair the efficient operation of the structure they were intended to protect. For example, trashracks at hydro-electric power plant intakes cause head loss so that bar spacing requirements to prevent debris entry into the turbines must be balanced against the loss of potential energy for power generation.

Wallerstein et al. (1996) reviewed current debris management technologies that are employed at various run-of-river structures in Europe and the USA. The study was conducted through

field visits and discussions with engineers and plant operators. Relevant published research work on debris control mechanisms, including trash rack design problems, raking equipment and spillway design was also reviewed.

The European research centres visited were Delft Hydraulics in the Netherlands, The Hydraulics Laboratory at the Technical University of Munich, Germany, and the Institute of Hydraulics, Hydrology and Glaciology at the Technical University of Zurich, Switzerland. The US field visits were carried out in Eastern, Central and south-central USA in the Huntington, Vicksburg, St. Louis and Louisville Corps of Engineers Districts.

In chapter five the control technologies are summarised, and state-of-the-art design procedures and best practice management recommendations for debris control outlined for each class of structure that may experience debris build-up problems.

Also presented here is a summary outline of a computer program which calculates the probability of debris build-up at bridge piers, and the associated debris induced scour. This program incorporates the theoretical models developed by Melville and Dongol (1992) and Simons and Li (1979).

2 LITERATURE REVIEW

2.1 Introduction

Organic or woody debris is an important channel independent variable in many fluvial systems (Hogan, 1987). For example, Bevan (1948; quoted in Keller and Macdonald, 1995) concluded that in the Middle Fork Willamette River, Oregon woody debris was responsible for more channel changes than any other factor.

In a literature review of published material then available, Hickin (1984) suggested that vegetation may influence channel processes through five mechanisms:

a) Flow resistance

b) Bank strength

c) Bar sedimentation

d) Formation of log jams

e) Concave-bank bench deposits

Hogan also identified that the literature concerning this subject was of two main types: that dealing with the indirect influence relations between vegetation, water, sediment yields and river morphology; and that dealing with the direct impacts of channel vegetation on channel morphology.

Since the 1980s the number of papers dealing with vegetation in rivers has increased markedly, however, including a number of studies concerning Coarse Woody Debris (CWD), (Nakamura & Swanson, 1993), Large Organic Debris (LOD) (Hogan, 1987) or Large Woody Debris (LWD), (Smith & Shields, 1992) and the accumulation of debris jams or dams in river channels.

Studies can be grouped by topic into those dealing primarily with :

a) Input processes, distribution and residence time of LWD;

b) Geomorphic significance of LWD;

c) Ecological impact of LWD;

The physical processes involved in each topic vary depending upon the size of the stream relative to that of the CWD (Nakamura et al., 1993).

Most studies have been carried out in stable channel environments in the US, Canadian Pacific Northwest, UK, and New Zealand. Instability, in the form of landsliding, is cited by Pearce & Watson (1981) as a means for debris to enter channels, but, more generally, the study of debris impacts in inherently unstable channels has not been addressed.

1.2 Input Processes, Formation and Residence Time of LWD

2.2.1 Input processes

Large Organic Debris enters river systems by two main processes; either from outside the channel due to bank erosion, mass wasting, windthrow, collapse of trees due to ice loading or biological factors such as death and litter fall (Keller, 1979); or from inside the channel, through erosion and flotation of emergent and riparian trees (Hogan, 1987). Fetherston et al. (1995) suggest that debris inputs are either "chronic or episodic". Chronic inputs are frequent but small in magnitude and occur due to tree mortality and bank failure, while episodic inputs are infrequent but provide a large amount of material. Episodic input processes include windthrow, ice storm, fire and flood events. The importance of different input processes varies widely. For example, 45 percent of input is due to windthrow in the Lymington Basin, UK (Gregory et. al, 1993), while massive inputs from landsliding of debris in a mountain catchment are reported by Pearce & Watson (1983), and by lansliding as a consequence of logging operations in the Queen Charlotte Island, British Columbia by Hogan et al. (1995). Keller et al. (1979) suggest that in low gradient, meandering streams inputs are predominantly the result of bank erosion and mass bank wasting, windthrow and ice loading, while in mountain streams the main process is debris avalanche. Diehl & Bryan (1994) found the dominant input process to be bank erosion in unstable rivers in Tennessee and noted that channel instability could be a good indicator of in-channel debris abundance. LWD that has been input by bank erosion can be identified and distinguished from that which has entered by other processes because the trees will usually have an asymmetrical root mass due to progressive slipping of the tree from the bank into the channel (Diehl & Bryan, 1994). Smith et al. (1993) found debris input to be spatially random. However, the locations of zones from which LWD is supplied will vary as a function of the distribution of riparian vegetation, streamside topography, channel characteristics and the prevailing wind strength and direction, (Fetherston et al., 1995). It may therefore be possible to determine which are the dominant input factors based on observations of these factors and, thereby, predict the distribution of major source areas within the catchment.

2.2.2 Formation of jams

Once in a channel, debris may form into jams or dams. Jams usually form around "key coarse woody debris" (Nakamura, 1993), which are usually large, whole trees that have entered the channel by one of the mechanisms mentioned above and which may be anchored to the bed or

banks at one or both ends. Smaller debris floating down the channel then accumulates against the key elements, which acts as a sieve in trapping debris and, later, sediment. If there is no fine debris in the stream a mature jam may never form, so that the impact of key-debris is minimal. The location of debris jams within the channel, their size and their coherence vary as functions of position in the catchment. In small streams much debris will accumulate where it falls because the flow is not competent to move coarse material, and it is in larger streams that distinct jams may form. Conversely, in larger rivers debris may not accumulate because the river is competant to carry it away downstream. Piegay (1993) observed debris distribution in a sixth order river in France and found that most material was deposited on the channel margins, forming a narrow debris line rather than in-flow jams. Wallance & Benke (1984) noted a similar distribution in meandering rivers in the southeast USA where dense, partial jams formed at a angle to the main flow. As mean channel dimensions and flow competence increase downstream more and more debris will be moved from its position of input, until all but the largest trees are transported. This process relationship may result in a trend of reducing LWD frequency downstream, but, at the same time, an increase in the volumetric size of each jam (Swanson et al., 1982).

2.2.3 Residence time of debris jams

The residence time, or persistence, of debris jams is an important factor, which determines the timespan over which channel morphology at a jam site will be affected. The influence exerted by jams on channel morphology also varies with time as the debris in the jam structure deteriorates (Hogan et al., 1995). Assessing residence time is difficult and estimates range between 12 months, for a 36% change or removal (Gregory and Gurnell (1985), to 40-90 years (Hogan, 1987), to 200 years for streams in British Columbia (Keller & Tally, 1979). Residence times may vary as a function of drainage basin area, and are largely dependent upon the return period of a flood with a magnitude which is capable of entraining a significant proportion of the trapped debris or moving larger key components of the jam. Other important factors affecting jam persistence are average tree dimensions and wood deterioration rate. Swanson et al. (1982) discovered that the density and volume of in-channel debris are greater in rivers which flow through coniferous forests than it is in those that flow though deciduous forests. This is because conifers are, on average, taller and have slower decay rates than deciduous trees.

2.3 Geomorphic Significance of LWD

2.3.1 Effects of channel scale

It is important to recognise that processes are scale-dependent and that the influence of LWD on channel and valley morphology may change systematically downstream through the drainage network (Abbe & Montgomery, 1993). Zimmerman et al. (1967) found that debris accumulations in a very small stream completely obscured the usual hydraulic geometry relations, while Robinson & Beschta (1990), and Keller & Tally (1979) suggest that debris loadings increase with stream size. Gregory et al. (1985), have characterised jams into three types :

1) Active (form a complete barrier to water and sediment movement, and create a distinct step or fall in the channel profile);
2) Complete (a complete barrier to water/sediment movement, but no step formed);
3) Partial (only a partial barrier to flow).

They suggest that these types become sequentially more prevalent as channel size increases.

Once trees fall into a stream, their influence on channel form and process may be quite different from that when they were on the banks, changing from stabilising to destabilising through causing local bed scour and basal erosion of the banks. Thus, jams represent a type of auto-diversion, that is, a change in channel morphology triggered by the fluvial process itself (Keller & Swanson, 1979). The type and degree of impact on channel morphology depends primarily on the channel width/tree height ratio and on debris orientation relative to the flow. Mean discharge and the dominant discharge recurrence interval are also important because the higher the flow is relative to jam size, the smaller will be the jam's impact in terms of acting as a flow diverter and roughness element. The principal effects of debris upon channel morphology are described below.

2.3.2 Impact of debris jams upon channel morphology

LWD influences the geomorphology of rivers on three levels (Gray, 1974); the overall channel form; detailed features of the channel topography; and channel roughness.

Heede (1985), Smith (1993), Andrus et al. (1988) and Mosley (1981) have all observed that the spatial distribution and number of pools, riffles and gravel bars is positively related to the distribution and volume of LWD in the channel. This relationship has been explained through laboratory experiments by Smith & Beschta (1994), who found that the pool-riffle sequence in

gravel-bed rivers is maintained by a combination of mean boundary shear stress and intermittent lift and drag forces due to velocity fluctuations around debris. Random debris input will also distort the pool-riffle sequence, making it less systematic, so that the long-profile has very little spatial memory, or periodicity (Robinson & Beschta, 1990). Robinson and Beschta (1990) devised a pool classification system, containing six pool categories (lateral scour, fluvial, plunge, underflow, deflector and dam) based on flow and debris. Other studies have shown that a considerable proportion of the vertical fall of channels can occur at the sites of debris jams, accounting for a 4% of the vertical drop along a 412m reach of channel in Vermont (Thompson, 1995) and 60% of the total drop in Little Lost Man Creek in Northern California (Keller & Tally, 1979). Debris jams, therefore, act as local base levels and sediment storage zones which provide a buffer in the sediment routing system (Heede, 1985, Bilby, 1981). Thompson (1995) found that LWD causes an important negative feedback mechanism, where, in the case of channel degradation, there is an increase in debris input due to mass bank failure, which in turn causes greater sediment storage. Channel bed elevation is consequently raised once more and the rate of bank failure and debris input is thereby reduced. On this basis, Klein et al. (1987) argue that jam removal can reduce the base level for the channel upstream and may trigger bank erosion. However, in an experimental study by Smith et al. (1993a and b) it was found that, while the removal of debris from a small gravel bed stream initially caused a four fold increase in bed load transport at bankfull flow, the associated loss of scour turbulence and greater flow resistance imparted by alternate bars actually resulted in a reduction in stream power which was compensated for by sediment deposition and net channel aggredation.

Potential energy is dissipated at jams, with energy loss being as much as 6% of total potential energy (MacDonald et al., 1982). Shields & Smith (1992) found that the Darcy-Weisbach friction factor was 400 % higher at base flow in an uncleared river reach compared to a clear condition, but that this difference declined to 35% at high flows. The velocity distribution is also far more heterogeneous in debris-filled reaches, especially at low flow. Changes of stream power distribution due to flow resistance effects in turn give jams the ability to influence the location of erosional and depositional processes. Also, the backwater effect created by jam back-pools may induce local silting (Keller et al. 1976). Thus, in small, stable channels, log steps generally increase bank stability and reduce sediment transport rates by creating falls, runs and hydraulic jumps. The localised dissipation of energy can, however, result in

associated local scour and bank erosion which causes channel widening. Bank failure may also occur through flow diversion around a debris obstruction (Murgatroyd & Ternan, 1983). Davis & Gregory (1994) have also suggested a mechanism whereby bank failure is induced through the erosion of a porous, gravel, bank subsurface due to the greater hydrostatic pressure caused by debris dammed flow. Conversely, Keller & Tally (1979) have observed that flow convergence under logs may cause channel narrowing, with sediment storage upstream and a scour-pool downstream of the log step.

As drainage area increases, and the channel width/tree size ratio exceeds unity, flow is diverted laterally, inducing bank erosion through local basal scour. Hogan (1987) found that in undisturbed channels in British Columbia organic debris orientated diagonally across the channel resulted in high width and depth variability. However, in catchments where there had been logging operations the majority of in-channel discarded timber was orientated parallel to the flow and it subsequently became incorporated into the stream banks, protecting them from erosion. Nakamura & Swanson (1993) and Keller & Swanson (1979) have suggested that there is a progression of types of interaction between debris jam and channel processes, ranging from local base level control and possible local widening in low-order streams, to lateral channel shifts and even meander cut-off in middle-order channels, where debris is moved into larger more coherent jams which may either increase or decrease the channel stability depending upon the erodibility of bed and banks. In larger channels still, bars may form and flow bifurcate around debris obstructions. This last process has been documented by Nanson (1981) in British Columbia, who found that organic debris deposited at low flow provided the nuclei for development of scroll bars, through the local reduction of stream power. Hickin (1984) also observed crib-like bar-head features, but was undecided regarding whether the debris caused bar formation, or whether the bars pre-dated and trapped the debris. In either case, organic debris would enhance sediment deposition and bar formation.

2.4 Ecological Impact of LWD

LWD dams are very important in small stream ecosystems because they provide a source of organic matter and retain floating leaves and twigs in the dam structure and backwater pools. This coarse particulate organic matter (CPOM) is broken down in the low energy pool environment by shredder invertebrates, creating fine particulate organic matter (FPOM) and dissolved organic matter (DOM), which are the required energy sources of a succession of invertebrate species who are, in turn, the energy source of high fauna species. Bilby & Likens

(1980) found that the percentage of the standing stock of organic matter retained by jams changed from 75% in first order, to 58% in second order, to 20% in third order streams because the prevalence of dam type jams declined downstream. The volume of CPOM therefore declines downstream, while the volume of FPOM and DOM increases. This gives rise to a spatially varied invertebrate community, changing from shredders in small channels to gathers of FPOM downstream. Smock et al. (1989) and Wallance & Benke (1984) found similar correlations between debris volume and invertebrate abundance in sand-bed streams, where debris provides the only stable substrate for organic matter retention and invertebrate habitat. Higher species, such as fish, use debris and associated pools for shade, protection from predators, feeding and spawning grounds. The pools and falls created by log steps also help to oxygenate the flow, and provide a variety of different energy environments which are can be colonised by niche species.

In addition to providing essential fauna habitat, LWD is also a vital factor in the development of the riparian forest mosaic (Fetherston et al., 1995). Debris deposition in the channel and on the floodplain creates sites of low boundary shear-stress where vegetation colonisation can take place. This leads to the development of vegetation stabilised islands and bars (affecting the geomorphological development of the channel) which may subsequently coalesce and/or become attached to the bankline to form new areas of forested floodplain that provide shade, bank stability and supply and storage of organic matter, sediment, water and new LWD.

2.5 Management Strategies

Until basic research concerning in-channel LWD began to suggest otherwise, it was reasonably believed that LWD was detrimental to the fluvial system, hydraulically, ecologically and geomorphically. On this basis, reasons for debris removal included :

a) To improve navigation;

b) To increase channel conveyance by reducing roughness;

c) To eliminate bank erosion;

d) To facilitate the migration of fish, especially salmon (MacDonald, 1982).

It is now recognised that there are advantages to be gained by maintaining or even increasing in-channel debris accumulations (Gregory & Davis, 1992; Keller & McDonald, 1995). Management strategies that are currently advocated vary widely, however. This reflects our, currently incomplete understanding of LWD dynamics in different channel environments, and

occurs because goals vary between different management strategies. In this respect effective debris management depends on the underlying aims of the proposed management action.

Successful management also depends upon a comprehensive understanding of the following engineering-geomorphologic factors (Gregory & Davis, 1992)

a) The relationship between river channel processes and river channel morphology;

b) Awareness of the timescales over which river channels may adjust;

c) Consideration of channel management in the wider context of river basin management.

Specifically, debris management must consider :

a) Channel stream power characteristics;

b) Sediment movement and storage relationships (high/low; fine/coarse sediment; suspended/bedload);

c) Channel stability;

d) Size and character of river channel in relation to debris size;

e) Spacing and frequency of jams;

f) Size and character of jams, and orientations of component material;

7) Age and stability of component materials.

In an evaluation of soft engineering for in-stream structures (including some using woody debris) to mitigate the effects of highway construction in British Columbia, Miles (1995) found that nearly 50% of the structures had been severely damaged after 8 to 14 years. Miles attributed this problem to insufficient understanding and consideration of the stability of the structures in a high energy river environment. He concluded that soft restoration techniques may not be appropriate in high energy mountain rivers and that, if restoration is to be performed, funding must be made available for long-term monitoring and maintenance.

There appears, in general, to be a consensus of opinion amongst researchers interested in LWD regarding appropriate management approaches for channel restoration. Bren (1993) and Nunnally (1978) argued that the riparian zone should be left undisturbed, in a natural state (although defining natural is difficult in most channels) and that, because debris is so important for the river ecosystem, debris jams should be left in place. Keller and McDonald (1995) studied catchments which had been disturbed by logging operations. They recommended that a riparian buffer strip should be left to maintain the natural LWD supply and warned that landsliding events caused by poorly exectuted logging operations, can cause excessive LWD

input which is detrimental to stream habitat and flow and sediment conveyance. There may be a case in streams lacking a wooded riparian strip to suggest the introduction of artificial debris jams (Keller & McDonald, 1995). If a debris recharge policy is to be implemented, however, it is important that debris jam volume and orientation emulates the values which would be found under natural conditions (Robinson & Beschta, 1990). Wallace & Benke (1984) concluded that, in most instances, the best management is probably no management except where adjacent floodplains have to be protected from flooding.

Comprehensive studies of coarse woody debris in relation to river channel management have been carried out by Gregory and Davis (1992) and Gurnell and Gregory (1995a and b). Gregory & Davis (1992) produced a preliminary table of debris management criteria (see figure 2.1) based upon the findings of twenty two research papers and primary field studies carried out in the New Forest, UK. They conclude that "... a conservative approach to debris removal should be adopted for most areas, but that different strategies are needed according to the characteristics of particular localities" (Gregory and Davis, 1992, pg. 133).

It should be noted, however, that this study, in common with most others cited above, was carried out in an essentially stable, equilibrium channel environment where changes to channel morphology are negligible and significant LWD impacts relate mostly to ecological habitat diversity. Also, little attention is paid to the "different strategies" that may be required in contrasting channel environments and there is no discussion of conflicts between practices advocated by various organisations in the USA. For example, Gregory & Davis (1992) suggest that, based on their literature survey, no debris should be removed from channels exhibiting low stability (Figure 1.1). However, this contradicts the practice described by Brookes (1985, pg. 64), "In North America the concept of channel restoration was developed in North Carolina under the funding of the Water Resources Research Institute of the State University ...Restoration is achieved by removing debris jams and providing uniform channel cross-sections and gradients whilst preserving meanders, leaving as many trees as possible along the stream banks, and stabilising banks with vegetation and rip-rap where necessary ...". Similar approaches, have been documented and carried out by numerous researchers and organisations in the USA, including; McConnel et al. (1980), based upon work on the Wolf River, Tennessee; the American Fisheries Society (1983), in a publication entitled "Stream Obstruction Removal Guidelines"; Shields and Nunnally (1984); and Palmiter (Institute of Environmental Sciences, 1982).

The recommendations of Palmiter (1982) include the following :

a) Removal of log-jam material by cutting it to a manageable size;

b) Protection of eroding banks using brush piles and log-jam material, with rope and wire;

c) Removal of sand and gravel using brush-pile deflectors;

d) Revegetation to stabilise banks and shade-out aquatic plants;

e) Removal of potential obstructions such as trees and branches;

Willeke & Baldwin (1984) assessed the Palmiter techniques and found them suitable for areas experiencing chronic, low intensity flooding and bank erosion, but not advisable for rivers with extreme flood problems. They are also found to be largely ineffective for erosion control where the mechanism of bank failure is that of mass wasting rather than tractive force erosion (Hasselwander, 1989).

It is evident from the preceding discussion of LWD management strategies that recommendations vary considerably from limited or no interference, to total clearance of debris from the channel. These apparently contradictory recommendations must be viewed in the light of the overall management programme that they were designed for, as requirements for habitat enhancement differ from those for flood defence.

Finally, and of great importance, is the fact that the recommendations of type made by Palmiter and others, address debris management predominantly in low gradient, sand-bed, perhaps unstable and flood prone rivers (South East USA), while those prescribed by Gregory and Davis (1992) and others are based upon findings from upland (even mountain), gravel-bed rivers and streams (Pacific Northwest USA). Process relationships between the debris and the channel are likely to differ between these two types of fluvial environment although, as yet, these differences have not been recognised or investigated. Indeed, while there is a wealth of research concerning the geomorphological impacts of LWD in upland gravel-bed rivers, there has been little comparable research in lowland, sand-bed, and/or unstable river environments.

Figure 2.1 Determinants for a management strategy for rivers in woodland areas (modified from Gregory and Davis, 1992)

	CHANNEL VARIABLE	MANAGEMENT STRATEGY: CHANNEL CLEARANCE	PARTIAL DEBRIS CLEARANCE	NO REMOVAL	LIMITED DEBRIS CLEARANCE
CHANNEL ENVIRONMENT	Stream Power			high	
			low		
	Sediment Storage and Tansport			high	
			low		
	Channel Width / Tree Height		high > 1		
				low < 1	
	Channel Stability		high		
				low	
	Adjacent Landuse Value	high value agricultural	grazing	managed / old growth forest	
DEBRIS ENVIRONMENT	Spacing and Frequency of Dams	excessive	high	natural levels	low >5 - 10 channel widths
	Debris Budget Loading	excessive	high	natural levels	low
	Size and Character of Coarse Debris		< 10 cm diameter		
				> 10 cm diameter	
			green foilage		
	Size of Blockage	> 10 channel widths long, debris jam	> 5 channel widths long	active debris dam	partial debris dam
	Anchorage of Debris	no anchorage	single end anchorage	both ends anchored	
	Stability of Debris	low	moderate	high	
	Orientation of Debris to Flow	60-90 degrees		parallel to flow	
	Residence Time of Logging Debris	24 hrs		> 5 yrs since introduction	
IMPACTS	Habitat Diversity	low		high	needs enhancing
	Aesthetics	low importance		high importance	
	Blockage to Fish Migration	possible		negligable	

3 HYDRAULIC SIGNIFICANCE OF LWD

A comprehensive investigation of the hydraulic effect of LWD in rivers has not been performed. However some studies have investigated the effect of LWD on channel roughness, the hydrograph, velocity distribution and water surface profile.

3.1 Effect of LWD on Channel Roughness

The Manning "n" equation generates a roughness coefficient representing all sources of flow resistance in the channel. This equation is widely used by river engineers who estimate values of "n" from tables in Chow (1959) or from photographs in Barnes (1967). The Manning "n" is defined as :

$$n = \frac{R^{2/3} S^{1/2}}{V} \qquad \text{or} \qquad n = \frac{1.49}{V} R^{2/3} S^{1/2} \qquad 3.1$$

where : R = hydraulic radius (m); S = energy slope; V = mean velocity (ms^{-1}); 1.49 = conversion to fps units.

The range of "n" values in alluvial channels is from 0.025 to 0.15. For heavily congested streams less than 30m wide "n" ranges from 0.075 to 0.15. Irregular and rough reaches of large streams have values of "n" from 0.035 to 0.10. The Manning equation was developed empirically to describe open channel situations with fully turbulent flow where friction is controlled by drag from the channels surface. The equation attaches significance to the hydraulic radius which may be irrelevant if the channel is heavily choked with LWD. The hydraulic effect of LWD varies as a function of relative depth of flow. Bevan et al. (1979) found that when LWD is high in relation to flow depth the roughness coefficient is extremely high (Manning "n" >1). As LWD becomes submerged it exerts less influence on flow hydraulics. The Manning equation is therefore, inappropriate in situations where there is a high degree of obstruction in the channel, particularly where n >1.

Shields and Smith (1992) measured a large decrease in Darcy-Weisbach friction factor as discharge increased, and also observed that friction factors, for cleared and uncleared reaches, converged at high flows. Indirect evidence for these findings is provided by investigations of downstream hydraulic geometry which show that roughness generally decreases as channel size increases (Wolman, 1955). Petryk and Bosmajian (1975) derived the following equation to predict Manning "n" as a function of density of vegetation in the channel, hydraulic radius, Manning "n" due to boundary roughness and a vegetation drag coefficient:

$$n = n_b \sqrt{1 + \frac{Cd \sum Ai}{2gAl} \left[\frac{1.49}{n_b}\right]^2 \left[\frac{A}{P}\right]^{2/3}} \qquad 3.2$$

where : n_b = Manning's boundary roughness coefficient excluding the effect of vegetation; Cd = drag coefficient for vegetation (assumed to be 1); Ai = projected area of the ith plant in the streamwise direction; A = cross-sectional area of flow; L = length of the channel reach being considered; P = wetted perimeter of channel. In this formula the expression CdΣAi/AL represents the density of vegetation in the channel.

Gippel et al. (1992) note that a problem with this formula is in selecting a value for the drag coefficient, Cd. Petryk and Bosmajian assumed a value of 1, but this applies to cylinders in infinite flow. In streams, interference from nearby obstructions and the effect of blockage on the drag coefficient should also be considered.

Smith and Shields (1992) studied the effects of varying levels of LWD density on the physical aquatic habitat of South Fork Obion River, Tennessee, USA. Two secondary objectives in this study were to develop and demonstrate a method for quantifying LWD in a given reach and to relate the quantity of LWD to reach hydraulics. An approach similar to that used by Petryk and Bosmajian (1975) was used to calculate the effect of LWD on channel roughness. The LWD density in a reach was calculated using the following formula :

$$DA = \sum_{i=1}^{n} \frac{A_i}{A} L_r = (1/L_r) \sum_{j=A}^{D} F_{bj} \sum_{k=1}^{3} N_{j,k} F_{wk} \qquad 3.3$$

where : n = total number of LWD formations in the reach; A_i = area of the ith debris formation in the plane perpendicular to flow; A = reach mean flow cross-sectional area; L_r = reach length; F_{bj} = formation type weighting factor for jth formation type; $N_{j,k}$ = number of type j LWD formations in Kth width category; F_{wk} = weighting factor based on LWD formation width category.

Rather than Using Manning's n, the more theoretically based Darcy-Weisbach flow resistance equation was used, which can be expressed as:

$$f = \frac{8gRS_w}{V^2} \qquad 3.4$$

where : f = Darcy-Weisbach friction factor; R = hydraulic radius; S_w = water surface slope

In a channel reach where LWD plays a major role in flow resistance, total resistance can be expressed as:

$$f_t = f_b + f_d \qquad 3.5$$

where : f_t = total Darcy-Weisbach friction factor; f_b = boundary friction factor excluding LWD effects; f_d = friction factor due to LWD.

Total head loss is the sum of a boundary friction loss and a LWD blockage loss, as follows:

$$h_L = S_E L = \frac{\left[\left(f_b L / 4R\right) + K_d\right] V^2}{2g} \qquad 3.6$$

where : h_L= total head loss; S_E = slope of the energy gradient; K_d = dimensionless loss coefficient (dependent upon LWD density).

The energy slope can be calculated using a total friction factor from the Darcy-Weisbach equation:

$$S_E = \frac{f_t V^2}{(8gR)} \qquad 3.7$$

Substituting this expression for S_E into equation 3.6 gives:

$$f_t = f_b + \frac{4RK_d}{L} \qquad 3.8$$

Therefore:

$$f_d = \frac{4RK_d}{L} \qquad 3.9$$

The ratio K_d/L may be expressed in terms of the LWD density as:

$$K_d / L = DA \qquad 1.10$$

Smith and Shields calculated values for f_b using curves developed by Alam and Kennedy (1969) and hydraulic parameters determined from dye tracer tests in the LWD reaches, which provide direct discharge and velocity estimates (Richards 1982), and the median bed grain size determined from sieve analysis. Values for f_d were then calculated using equations 1.3, 1.9 and 1.10. They then compared computed values of f_t with values measured using dye tests.

The results of their study showed a reasonable positive correlation between the measured and computed friction factors. However, they recognise that considerable refinement and site-specific adaptation may be in order, and that the method does not account for local energy loss because of bends or flow expansion and contraction at bridges, debris dams, or riffles. The method does have a sound theoretical basis, however, and could be usefully employed in future studies of LWD hydraulics.

3.2 Effect of LWD on velocity distribution

LWD clearly influences the direction and magnitude of flows currents within stream flow, but few data have been documented in the literature. Swanson (1979) produced detailed maps of debris jams indicating flow with directional arrows. Smith and Shields (1990) reported that the removal of

LWD from a river 18-23m wide, 3.5 to 4.5 m deep produced more uniform flow, with less of the channel being occupied by eddies or regions of reduced velocity.

3.3 Effect of LWD on Stage/Discharge Relationships, the Hydrograph and Flood Frequency

LWD is often removed because it is assumed that this will achieve a significant reduction in channel roughness which will allow a higher mean flow velocity and, thereby, increased channel flood capacity. There is evidence to support this assumption. For example Smith and Shields (1990) measured the mean flow velocity in two cleared reaches of a river to be 0.40 m/s and 0.34 m/s. In an uncleared reach of the same river the mean velocity was 0.27 m/s. MacDonald and Keller (1987) also found that there was a local increase in velocity by up to 250% as a result of LWD removal and a decreased sinuosity of the low flow thalweg. According to Gippel et al. (1992) the Murray-Darling Basin Commission calculated a theoretical reduction in water level of 0.3 - 0.4 m after the removal of approximately 200 snags per kilometre. However, later analysis of flow records indicated a reduction of only 0.2 m. In theory, there should be a statistical reduction in the magnitude and frequency of overbank flooding where debris is removed from a channel because of the increased channel capacity. Bodron (1994) used a dynamic routing model to demonstrate changes in both stage and duration of flood events before and after LWD removal, using Manning n values calculated in the study by Smith and Shields at South Fork Obion River, West Tennessee. Despite the increase in channel cross-sectional area due to LWD removal being ignored, small reductions in flood height and duration were calculated based solely on the change in Manning "n" values. Bodron also notes that flood stage would be reduced further if sediment accumulations at each jam site had been removed. However, according to Gippel et al. (1992) many claims that this effect has been achieved lack any supportive evidence. Counterclaims also lack supportive evidence, because of the difficulty of isolating the hydraulic effect of LWD removal. It is even possible that LWD removal might increase flood peaks downstream, because the flood wave downstream is less attenuated. Gregory et al. (1985) found that LWD ponds water which results in an increase in water depth and a decrease in velocity, which, at low flows influences travel time significantly. At high flows, however, the ponding effect of LWD is drowned out. Shields and Nunnally (1984) noted that because large accumulations of LWD have a damming effect on the flow which locally elevates the base level, they can be treated as geometric elements within the channel, rather than simply as roughness elements, in backwater profile computations.

3.4 Modelling the Hydraulic Effect of LWD

Most studies of resistance to flow in rivers have concentrated on small-scale roughness, especially skin friction offered by bed sediments, where the size of the roughness element is small compared to the flow depth. LWD, on the other hand represents large-scale roughness, for which skin friction is small compared with form drag (Petryk and Bosmajian, 1975). Flow conditions associated with the presence of LWD in streams varies from sub-critical to super-critical depending on the dimensions of the LWD and the depth of water.

Gippel et al. (1992) used the momentum principle to determine the hydraulic effect of LWD, the effect being quantified in terms of afflux or backwater effect. If flow is subcritical (Froude number < 1), apart from local disturbance of the velocity profile, LWD only has an influence in the upstream direction. There are often practical difficulties with directly measuring the afflux at debris jams, however, an alternative to direct measurement is prediction on the basis of a known relationship between afflux and more easily measured parameters. Gippel et al. used the results of a laboratory hydraulic study to develop a method of determining the afflux caused by LWD.

They propose the use of the following equation to calculate afflux :

$$\Delta h = \frac{h_3\left[\left(F^2 - 1\right) + \sqrt{\left(F^2 - 1\right)^2 + 3C_D B F^2}\right]}{3} \qquad 3.11$$

where : Δh = afflux = $h_1 - h_3$ (m) and the drag coefficient :

$$C_D = \frac{F_D}{\frac{1}{2}\rho U_1^2 L_* d} \qquad 3.12$$

where : F_D = drag force (N); ρ = density of water (approx. 1000 kg/m^3); U_1 = mean velocity at section upstream of object (m/s); L_* = projected length of LWD in flow (m); d = diameter of LWD (m). and the Froude number:

$$F = \frac{U_3}{\sqrt{g h_3}} \qquad 3.13$$

where : U_3 = mean velocity at section downstream of object (m/s); h_3 = water depth downstream of LWD (m) and the blockage ratio:

$$B = L_* d / A \qquad 3.14$$

where : $A = W.h_1$ = cross-sectional area of flow (m^2).

Thus, the afflux depends on F, C_D and B. The Froude number can be calculated from direct measurement or from flow records. B can be found from survey. The problem in applying the equation centres on selecting an appropriate drag coefficient. The drag characteristics of a cylinder

in infinite flow are well known (Petryk and Bosmajian, 1975). Less is known about drag on cylinders within boundaries (the "blockage effect") where the drag coefficient is increased. Gippel et al. conducted experiments on LWD models to determine drag force, using a towing carriage and water tunnel. Froude number, LWD length to diameter ratio, and LWD depth from the bed all affected drag coefficient, but were much less important than the blockage effect, angle of orientation to the flow and the shielding effect (of one piece of LWD behind another). A suitable drag coefficient (C'_D) for the LWD in question can therefore be selected from their experimental results (Gippel et al. 1992, figures 3.8 or 3.12) on the basis of its overall shape and angle of orientation. The drag coefficient should then be adjusted for the blockage effect, which can be calculated using the following equation developed by Gippel et al. using their empirical data from flume studies :

$$C_D = C'_D (1-B)^{-3} \qquad 3.15$$

where : C'_D = drag coefficient in infinite flow.

These data are then substituted into equation 3.11 to calculate the afflux.

Predicted and measured afflux values resulting from the flume study were very closely correlated, and they conclude that the flume conditions did not seriously violate any of the assumptions in equation 3.11. The proposed method of afflux estimation was then applied to data collected from the Thomson River, Victoria, and revealed that de-snagging there would produce a reduction in stage of only 0.01m at bankfull flow.

In conclusion, this method of backwater, or afflux calculation due to individual items of LWD could be used as a tool to help determine whether the afflux reduction due to LWD removal would have a positive impact according to the perceived management requirements, or whether debris jams could be left in place, re-orientated, lopped or even re-introduced where sympathetic rehabilitation management is desirable.

Young (1991) carried out a series of experiments in a flume using scaled LWD pieces in order to determine the order of magnitude of the increase in flood levels caused by LWD at different positions within the channel cross-section. Results indicated that the frontal area of LWD, as a percentage of the channel cross-section, had to be very high in order to cause a significant rise in stage (a 10% stage rise required a frontal area of 80% of the channel cross-section area). LWD position variables were also examined. For example, it was found that LWD near the bed will cause a greater hydraulic effect than LWD higher in the cross-section, and that a 50 % reduction in the stage rise (from that due to LWD aligned perpendicular to the channel) requires a 40 degree

rotation of the LWD from the perpendicular. Young concluded that his results indicate that the amounts of LWD which are found in lowland rivers in Australia will seldom have a significant effect on flood levels, except where large log-jams form. However, he also notes that where rivers are used to supply irrigation water tolerances in water level are often lower and hence LWD removal may more frequently be necessary.

4 ENGINEERING-GEOMORPHIC ANALYSIS

4.1 Method

Data from the US Army Corps of Engineers DEC survey program, conducted in May 1994 and May 1995 has been used to locate significant debris jams, with respect to planform and long profile data on twenty three river reaches in the Yazoo Basin. The reaches surveyed are between 4000 and 12000 feet long and range in upstream basin area from between 3.5 to 150 square miles. A comprehensive understanding of debris dynamics can be attained from surveying these channels because reaches fall into several categories including, stable/unstable reaches, straight/meandering reaches and reaches which have either a predominantly agricultural or wooded riparian zone. The debris jams in each reach have been surveyed in detail to determine the mechanisms and locations of debris input, jam impact upon channel morphology and sediment routing and jam stability over time.

4.2 Results

Findings show that the dominant debris input mechanism is outer bank erosion at active meander bends (43%), followed by input due to channel instability (degradation and bank failure) (30%). Random input processes (windthrow, beaver activity and floated material) together account for only 37% of debris input in total. As debris input is not spatially random, major debris sources can be predicted using map-based data, by locating wooded riparian zones which coincide with either meandering or vertically unstable reaches.

The frequency of jams and volume of debris per unit reach length appears to only be very weakly related to watershed area (a surrogate of discharge), composite channel width and unit stream power, which are three potentially predictive independent variables. In channels with a catchment area greater than 50 square miles, coherent jams do not form as even the "key-debris" (whole mature trees) can be transported at the higher flows without becoming stuck in the channel. It appears, therefore, that there is a limiting catchment size (channel width) for jam formation, above which larger debris is supplied continually to downstream reaches.

Comparison of thalweg plots from reaches which have wooded riparian zones with those which have agricultural riparian zones shows that channel bed topography is much more irregular in wooded reaches. This is due, in the main, to debris-induced bed scour, and the deposition of sediment where debris causes energy dissipation. Debris filled reaches therefore offer a more diverse aquatic habitat for flora and fauna, than the uniform bed environment

found in debris-free reaches. Decomposing debris is also rich in organic carbon which is a vital food source for aquatic invertebrates (see Bilby & Likens, 1980).

Geomorphic field reconnaissance in the current and previous studies (Wallerstein & Thorne, 1994) indicates that the impact of debris jams varies primarily with jam orientation relative to the main flow direction. Impacts change from depth adjustment through scouring in small creeks, to width adjustment through lateral erosion in medium size streams, to negligible effects in the largest rivers. Processes therefore appear to be watershed-scale dependent and field evidence suggests that the ratio of average riparian tree height (TH) (potential debris) to channel width (W) can be used as an indicator of the likely impact that a jam will have on channel morphology and sediment routing. A debris classification system, modified from Robinson and Beschta (1989), has been used to describe the observed engineering-geomorphic impact of debris jams throughout the drainage network. The observed progression of jam types is as follows:

Underflow jams : in small catchments where fallen trees span the channel at bankfull level [$W < TH$]. Local bed scour may occur under debris at high flows, otherwise the in-channel geomorphic impact of the LWD is minimal.

Dam jams : in channels which the average tree height to channel width ratio is rough equal to one [$W \cong TH$], so that debris completely spans the channel cross-section. This type of jam causes significant local bank erosion and bed scour due to flow constriction, and backwater effects will cause sediment deposition in the lower energy environment upstream. Bars may also form immediately downstream of the jam.

Deflector jams : found where input debris does not quite span the channel [$W > TH$] so that flow is deflected against one or both of the banks causing localised bed scour and bank erosion. Subsequent bank failure results in the input of new LWD material to the reach so that the jam builds up further. Backwater sediment wedges and downstream bars may form at this type of jam provided that stream power is dissipated by the jam below the critical level for the bed load and suspended sediment transport.

Flow Parallel jams : found where channel width is significantly greater than the key-debris length [$W >> TH$], and flows are competent to rotate debris so that it lies parallel to the flow. Debris is also transported downstream in high flows and deposited against the bank-base on the outside of meander bends or at channel obstructions such as man-made structures. Related bank erosion and bed scour will be minimal, and bank toes may even be stabilised by debris

build-up. Flow parallel debris may also initiate or accelerate the formation of mid-channel and lateral bars.

The debris-induced, step-pool channel topography observed in many Pacific Northwest streams is not found in northern Mississippi as the fine grained bedload tends to pass through the open jam structure, and flow erodes under or around the debris. However, results do show that the net balance between debris-induced sediment retention and debris-induced bed scour is skewed in favour of sedimentation (total aggregate value of $98m^3$ excess sediment for all jam sites in all 23 reaches). Debris jams therefore help to stabilise reaches which are degrading. It must be noted, however, that debris-related sediment retention values are small, in comparison with total sediment yields from each reach.

Comparison between May 1994 and May 1995 thalweg data-sets shows that of the eighteen debris jams surveyed in May 1994 only one had been displaced by May 1995 while eleven new jams had formed in the intervening period. The formation of new jams can be attributed largely to debris input caused by channel bank instability. It appears, therefore, that debris jams are stable features in the short-term, although a better understanding of jam persistance can only be achieved through a long-term monitoring program.

4.3 Large Woody Debris Management Program

The relationships between LWD formations and channel processes, described briefly above, have been incorporated into the LWD Management Program (Wallerstein and Thorne, 1996). This program predicts the type of jam likely to be present in a given reach, determines its impact upon the channel morphology, and outlines an appropriate management strategy. Input data are those variables which have been found to be most critical in the LWD system and include channel width (determined from a catchment area function), average riparian tree height, reach sediment type and the riparian landuse type. The ratio of tree height to channel width is used to define the debris jam type present, with the precise limits of each classification determined from the empirical relationships developed from field studies. Sediment size is used to give an indication of the jam's potential to induce the formation of backwater sediment wedges or downstream bars. Debris jam types are classified using the scheme described section 4.2. The program output takes the form of a text file which describes the classification chosen, and suggests basic in-channel LWD management strategies. While the management strategies are based solely on theoretical considerations, the program never-the-less provides a

framework for future model development as empirical relationships between the variables are better characterised. A flow diagram of the computer program is shown in figure 4.1.

4.4 Debris Management Program Incorporating GIS

The management program has been linked to a GIS (Geographical Information System) front end which has been constructed by Peter Cheeseman, a masters student at Nottingham University (see Cheeseman, 1995). The project was carried out to demonstrate the potential for using GIS as a platform for data input to expert systems, to aid engineers with river basin management. The GIS was constructed in ARC Info using data layers supplied from the WES Intergraph data-base for the Abiaca Creek watershed. The system provides both automatic data input for the necessary variables, and a platform for running the program. The Abiaca Creek watershed was selected because it contains four debris survey reaches which are being monitored in the current research. The theoretical model can, therefore, be tested against the empirical data results from the field studies, and be validated and further developed.

The GIS is composed of four layers: the drainage network; road network; used to determine bridging points; landcover, which is split into agricultural, open water and wooded classifications, and channel sediment type. There is also a terrain model, which is used to calculate drainage basin area. Figure 4.2a shows a screen shot of the GIS, displaying the drainage network, roads and landcover, the toolbar and a help text box. The system incorporates a menu-driven interface which is used to display the data layers and perform analysis. On-line help files are also included. The analysis is performed by simply zooming in on the area of interest and clicking the mouse on the desired channel segment. The system then extracts the relevant values from its database for that location and passes them to an input file. The debris management program is then automatically activated and reads in the input file, calculates the results, and produces an output text file. This file is then read back into the GIS and displayed on the data screen. Figure 4.2b shows the GIS with a debris management output.

This management model is simple, to operate and provides a framework for future development as empirical relationships between variables are better characterised. As GIS becomes increasingly applied as a standard tool in watershed management, this will facilitate use of the GIS-based LWD Management Program.

Figure 4.1 LWD management program flow diagram

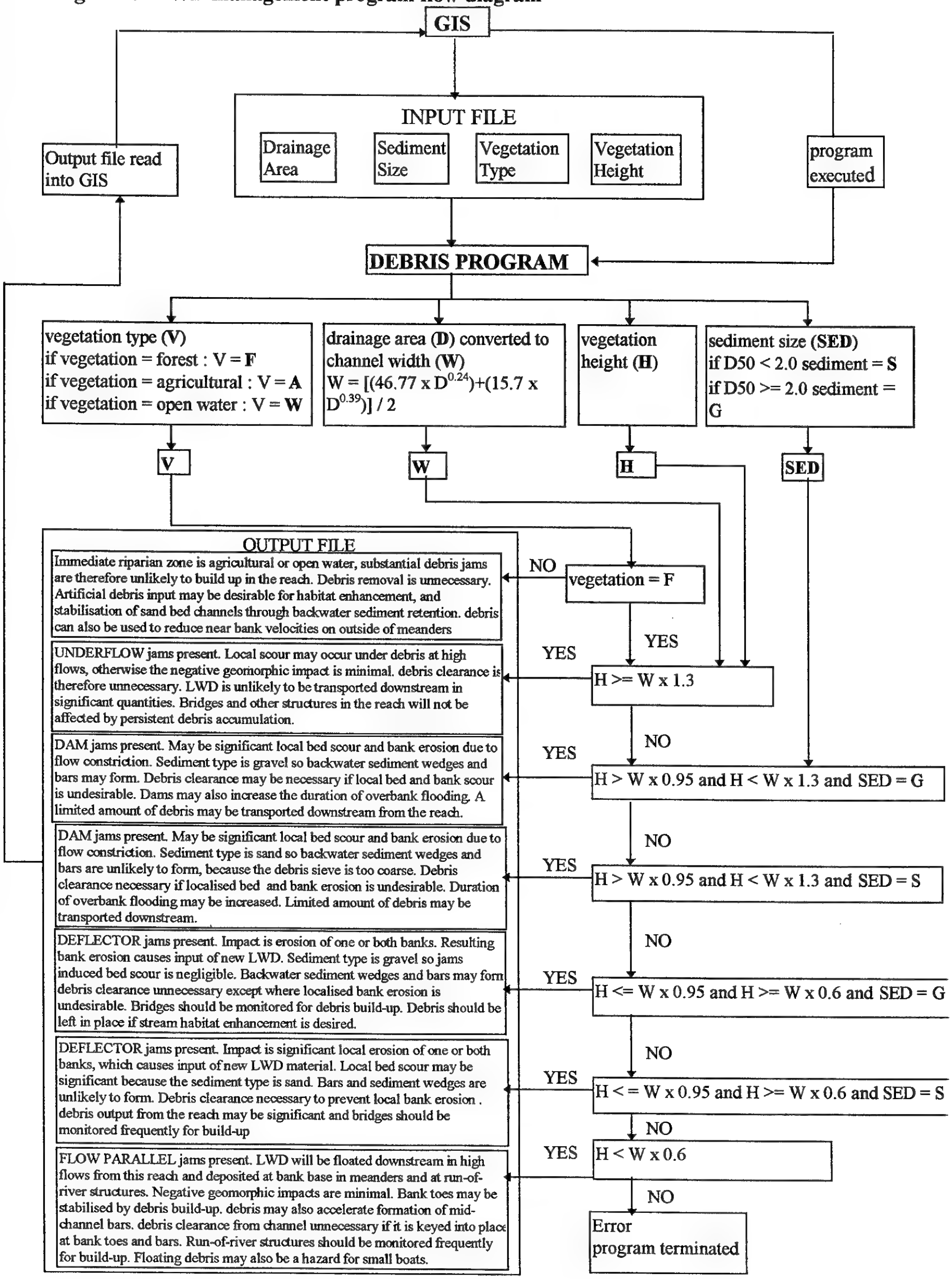


Figure 4.2a Abiaca Creek GIS showing watershed attribute layers and toolbar

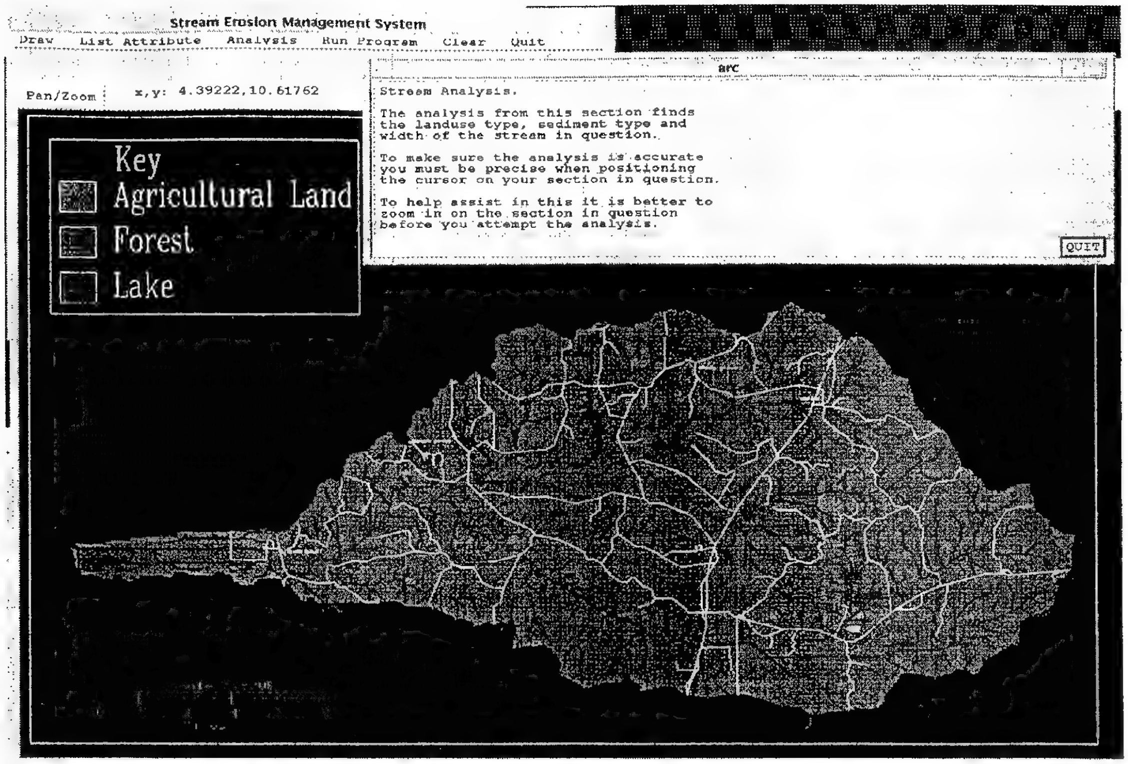


Figure 4.2b Abiaca Creek GIS showing Debris Management Output

5 DEBRIS AT HYDRAULIC STRUCTURES

A summary of best practice design and maintenance procedures for debris management at run of river structures, obtained from interviews, site visits and evaluation of all available literature, is presented here according to each type of structure discussed in Wallerstein et al. (1996).

5.1 In-channel Debris Retention Devices

These are can be very effective for combating debris transport from high yield source areas to important structures downstream. The "treibholzfang" device (refer to Wallerstein et al., 1996, section 1.2) that has been utilised in southern Germany is a very effective means of near-source debris control, if properly maintained. The use of this technology should be considered where debris transport causes acute problems at in-channel structures in the USA. The only drawback with such devices is their high initial cost (approximately $1.5 million) and the fact that they require a regular maintenance program to remove the collected debris.

5.2 Flow Diversion Tunnels

If large debris is to be passed through diversion tunnels then it is important that it is aligned parallel to the main flow direction. This may be achieved by using debris aligning piles, although care must be taken to avoid the possibility of debris straddling piles which could result in a catastrophic debris release into the tunnel during flood conditions. The alternative solution is to create the optimum flow approach conditions to reduce the potential for clogging the tunnel entrance. To achieve this solution it is worth considering the results obtained by Martin (1989) :

- Transition sections from natural channel to entrance channel should be curved to prevent flow separation and eddying;
- The approach configuration shown in figure 5.1a was highly effective in preventing blockage, because the radius allowed for debris to pivot into the tunnel;
- Configurations shown in figures 5.1a and 5.1b were the most hydraulically efficient for passing debris;
- Blunt edges and flat surfaces at or below the water surface tended to cause turbulence and to gather debris.

There is, however, no substitute for carrying out scale physical model tests when considering new tunnel approaches, using different approach and entrance designs and various, estimates of debris loadings. It is important to remember when carrying out such tests that there are scaling problems between model and prototype as simulated debris is likely to have different roughness, buoyancy and elastic properties to those encountered at full scale.

Figure 5.1a : Type 6 Design Approach (from Martin, 1989)

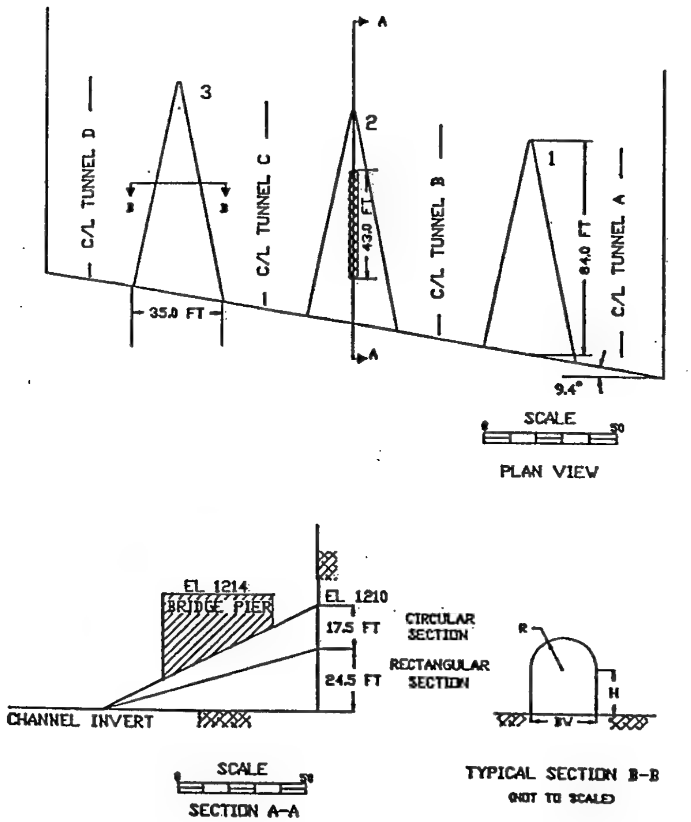
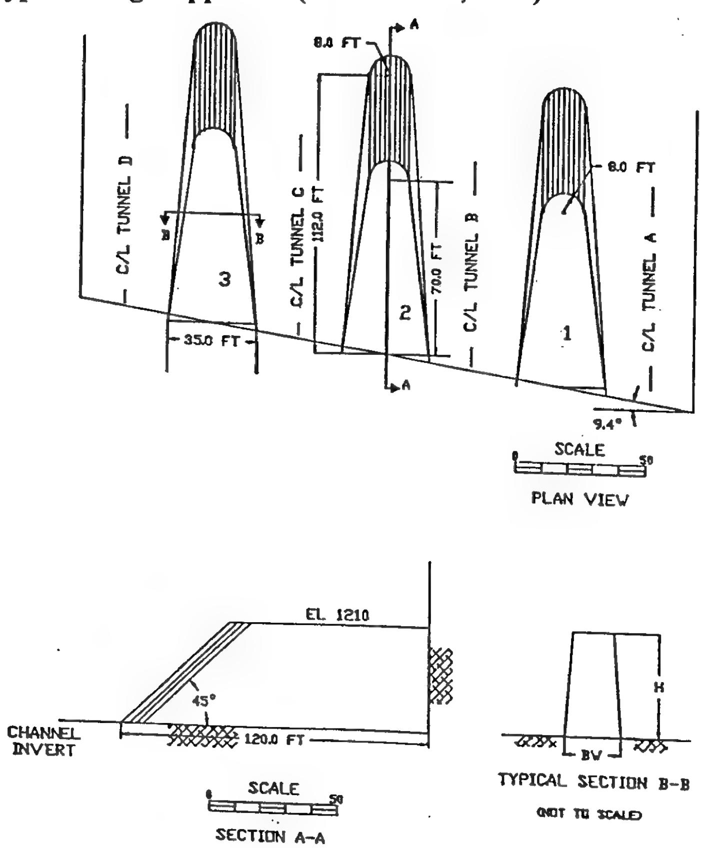


Figure 5.1b : Type 7 Design Approach (from Martin, 1989)



5.3 Lock and Dam Structures

Run of river lock and dam structures tend to have unique design and operating characteristics which make it difficult to develop a generalised set of recommendations for floating debris management. A customized approach is therefore normally taken at each structure. Procedures common to most structures, however, include the flushing of debris through the lock chamber or over the spillway, the use of booms and mule barges to divert debris to the desired area for conveyance, and the removal of non-essential parts of the structure that might collect debris when flood flows are expected.

The findings of a USACE study (refer to Martin, 1989) concluded that the amount of debris accumulating around intakes depends on the orientation and location of the locks, and the clearance between the invert and river bottom. Model studies, using simulated debris loads should therefore be considered an essential practice before the construction of new lock and dam facilities in order to obtain optimum flow approach conditions for debris passage or collection.

5.4 Spillways

Debris can be prevented from passing through spillways by using floating or fixed booms. These are not fail-safe measures, however as some material may get through this first line of defence in stormy conditions or when there are very heavy debris loads. If debris is to be passed through spillways Brushin et al. (1982) suggest that the following catchment factors should be carefully considered :

- Catchment hydrological and meteorological conditions;
- Potential for extreme flood events;
- Potential for mobilisation from high yield sediment and debris sources and upstream slope stability in forested areas.

Once potential debris loadings have been predicted the engineer should bare in mind the following recommendations (synthesised from Godtland and Tesakar, 1994, and Hartung and Knauss, 1976) to ensure safe debris passage:

- Horizontal pillar distance of bridge structures on top of spillway should be at least 80% of the length of the arriving trees;
- Vertical free opening between the crest and superstructure should be at least 15% of the tree length;
- Downstream height of sills should not exceed 1/3 of the tree length if a superstructure is present;

• Consider increasing the hydraulic capacity of spillways from the standard 1000 yr. flood to 5000 yr. flood and have enclosed tunnel diameters of 5 meters minimum;

• Clogging can best be avoided in closed conduits if there are smooth walls, no contractions or obstructions and no sharp bends;

• Intake discharge into spillway tunnels should be concentrated in one opening and the invert made as steep as possible to produce a fast flow that cannot be resisted by debris;

• Care must be taken to ensure that the design hydraulic capacity through the structure can be met even in the event of spillway gates becoming blocked. Drum, sector and flap gates are preferable to lift gates;

• Trashracks should never be used at spillways because clogging could potentially compromise the spillway design flood capacity.

5.5 Power Plant Intakes

Shallow and deep seated hydro power intakes can be protected from debris by various floating or fixed retaining devices located in the dam upstream the intake structure. Structures that have be used include floating booms, baffle walls, net and, in free flowing rivers, diversion dikes. The cost of such measures will vary with the size of intake to be protected and the potential debris loadings. Boom-type retaining devices are considered to be the first line of defence (Jansen et al., 1988) but trash racks are also required at most outlet structures. The following factors should be considered in trashrack design:

• The differential head across the rack and impact forces;

• Bar spacing: bars should be spaced so that the clear openings are not greater than the smallest opening in the conduit or turbine. As a rough guideline, for Kaplan turbines the clear spacing between bars should be no more than 1/30 the diameter of the runner, while for Impulse turbines the spacing should not be greater than 1/5 of the jet diameter at maximum needle opening (Zowski, 1960);

• Head loss at the rack: bars should be as thin as possible for hydraulic efficiency (flat end bars are normally adequate) but not less than 9.5mm at shallow intakes and 12mm for deeply submerged intakes. Semicircular trashrack seats (in planform) have been found to be the most efficient shape in terms of head loss reduction (Johnson, 1988). Head loss can be reduced at low pressure intake by inclining the trash rack between 15 and 45 degrees from the vertical;

• Vibration response: trashrack vibration can be subdivided into four areas; natural frequency of vertical and horizontal bars; excitation frequency; resonance; and fatigue. The von-Karmon effect can be alleviated by placing lateral stabilizers made from butyl rubber between bars and bracing;

• Trash rack maintenance and operation: fully submerged racks have less maintenance requirements than semi-submerged racks which must be easy to remove to facilitate repainting. Air bubblers may be necessary to clear racks of ice if the dam is susceptible to freezing. Adverse vortex generation at intakes should be tested for using scale models. Vortex problems can be overcome by using structural measures such as injector shafts.

5.6 Raking Devices

Unguided rakes have the advantage of being able to pass over obstructions without becoming jammed and they are also, generally, less costly than guided rakes. However, they are not being suited to deep intake structures where bars do not extend above the inlet structure and, if there are strong transverse currents, unguided rakes may become dislodged or overturned. Guided rakes can operate on vertical racks, are not affected by transverse currents and can operate on intakes where the trash rack does not extent to the unloading deck. Disadvantages are that the rake guides may become blocked by debris and, under severe debris conditions, may therefore need considerable maintenance work. Because of the operating limitations of mechanical rakes it may be preferable to use more simple types of rake which can be operated by a gantry crane mounted on the dam operating deck. Other debris removal systems available include collection boats, travelling screens (generally for fine debris at thermal power plant intakes), air bubblers and conveyors (refer to Perham, 1987).

5.7 Debris Disposal

Once collected debris must be disposed of in an acceptable fashion. The options available are: burning; burial; if low grade, use as firewood or chipped wood for horticultural purposes; if high grade, use for structural purposes. The latter two options are preferable as they may create some financial return for the operator, while burial is costly and burning is somewhat environmentally unsound, especially if the wood has become contaminated in the river by toxins, hydrocarbons, heavy metals, etc.

5.8 Debris at Bridges

In an investigation of bridge scour research needs, Jones et al. (1991) cited the affect of debris on pier scour depths as a subject of pressing concern that required model studies and field observations to characterise debris build-up. Doheny (1993) observed scour conditions at 876

highway bridges in Maryland, and, amongst other relationships, found that bridges in forested, urban and pasture basins were more prone to blockage than those in basins with row crops or swamp. Diehl & Bryan (1993) assessed potential debris volumes that could be transported to bridge sites in the West Harpeth River basin, Tennessee, and found bank instability to be the channel characteristic most useful in identifying channel reaches with high potential for production of LWD. Instability through channel migration, and mass failure or fluvial erosion can be detected on maps and aerial photographs (Diehl & Bryan, 1993). A study by Parola, Fenske & Hagerty was initiated to investigated the basin-wide impact of the 1993 Mississippi River Basin flooding on damage to the highway infrastructure. Structural geometry information as well as hydraulic information was collected at two sites where bridges collapsed at least partly as a result of debris loading, and was noted to be a contributing factor in the lateral load and scour of many bridges.

5.9 Methods for Managing Floating Debris at Bridges

Only one paper has been found that directly addresses debris management at bridges. Saunders & Oppenheimer (1993) believe that conventional methods of protecting piers from floating debris are inadequate. They comment that the use of pilings or some other barrier upstream of a bridge can actually exacerbate the problem because the debris accumulated may be released suddenly in storm conditions. They tested a new deflector, a lunate shaped hydrofoil which generates counter-rotating streamwise vortices in its wake which divert debris laterally to either side of the bridge pier. The deflector is positioned below the surface so that it is not impacted by debris upstream of the piers and so that the vortices migrate to the surface ahead of the pier. In flume tests the hydrofoil is reported to work very effectively and the device would appear to offer a possible approach to managing floating debris at bridges. However, if the average debris length is greater than the pier spacing debris floating with their long axis transverse to the flow are still likely to be trapped and the vortices might even turn flow-parallel debris through 90 degrees so that they become jammed between adjacent pier faces.

5.10 Modelling Bridge Scour with Debris Build-up

There are only a limited number of studies that have addressed the theoretical considerations of debris accumulation at bridges. Melville & Dongol (1992) look at the problem of pier scour due to debris, while Simons & Li (see Callander, 1980) have used a probabilistic approach to quantify the rate of bridge span blockage by debris and the subsequent backwater effect and pressure forces generated on the piers. Local scour at bridge piers has been extensively

investigated. However the impact of debris rafts at piers which create additional flow obstruction and therefore increase scour depths has been largely neglected. A design method for estimation of scour depths at piers is presented by Melville and Sutherland (1988), based on envelope curves from laboratory data. The largest local scour depth at a cylindrical pier is estimated to be 2.4D where D is the pier diameter. This value is reduced, however, using multiplying factors where clear-water scour conditions exist, the flow is relatively shallow, and the sediment size relatively coarse. In the case of non-cylindrical piers, additional multiplying factors are applied to account for piers shape and alignment. Consideration of the likelihood of debris build-up is not addressed by Melville and Dongol (1992) but they do note, however, that single cylindrical piers are the least likely shape to accumulate debris, and that the free space between columns is seldom great enough to pass debris. Prediction of the size of possible debris raft accumulations remains the biggest problem for accurate factor of safety calculations. The design curve for pier scour without debris accumulations, developed by Melville and Sutherland is described by the following two equations:

$$\frac{ds}{D} = 1.872\left[\frac{Y}{D}\right]^{0.255} \qquad \left[\frac{Y}{D} < 2.6\right] \tag{5.1}$$

$$\frac{ds}{D} = 2.4 \qquad \left[\frac{Y}{D} \geq 2.6\right] \tag{5.2}$$

where : D = pier diameter; ds = depth of scour; Y = approach flow depth.

This shows that scour depth increases with increasing flow depth towards a limiting value for Y/D>2.6. The same trend is found for piers with debris accumulations for values of Y/D<4. At higher values of Y/D scour depths decrease again because the proportion of pier length covered by debris decreases. For deep flows the effect of debris becomes insignificant and tends towards the value ds/D =2.4. The effective diameter of a pier with a debris accumulation, De, is given by:

$$De = \frac{Td^{*}Dd + (Y - Td^{*})D}{Y} \tag{5.3}$$

where : Td* = 0.52 Td; Td = depth of debris raft; Dd = debris raft length.

The factor 0.52 was determined by evaluating the limits of Td and Dd/D for the hypothetical case where D is assumed to be zero and the debris is assumed to extend to the base of the scour hole. D can therefore be substituted for De to calculate scour depth at piers with debris accumulations using the Melville and Sutherland design method. Conversely a maximum

allowable Td and Dd can be calculated by specifying an upper scour depth within an acceptable factor of safety for a given pier size.

4.11 Probability Based Debris Build-up Model

The rate of debris accumulation at a bridge is difficult to quantify. The only method found in the literature is that presented by Simons & Li (1979) in an MSc thesis by Callander (1980). According to Simons & Li, the trapping efficiency of a bridge is determined by:

1) Clearance beneath the bridge;

2) Span lengths;

3) Size and concentration of debris elements.

The following possible consequences are identified which can result from debris blockage:

1) Backwater effects;

2) Potential local flow diversion;

3) Channel avulsion;

4) Bridge failure.

Simons & Li express the volume of debris as a fraction of the sediment yield, and suggest a vegetation debris yield of 1%. In an attempt to estimate the number and volume of trees arriving at a bridge they utilise the volume of floodplain erosion necessary to yield a tree, and use a representative tree size for the watershed.

Trees are assumed to be cylindrical with a diameter Dt and a height Ht. The span between piers is Ls and the clearance between the water surface and the underside of the bridge is C. The chance that a tree will be trapped depends on a larger diameter however, Db, which represents either the canopy dimension or the root ball, whichever is larger.

If Ht > Ls the probability of at least one average tree being trapped is 100%. The blocked area is then estimated to be, NHtDt, where N is the equivalent number of average trees assumed to be trapped against the upstream face of the bridge. If Ht < Ls a probabilistic approach is used. Pt is the probability of a tree being trapped and as the blockage beneath a span increases so the chance of other trees being trapped increases. The probability of the first tree being trapped is assumed to be a ratio of half the tree diameter, Db, to the total waterway area beneath a span, LsC:

$$PT1 = \frac{\frac{1}{2}\left(\pi Db^2 / 4\right)}{LsC} = \frac{\pi}{8}\frac{Db^2}{LsC} \qquad 5.4$$

Li (see Callander, 1980) observed that a tree caught on a pier will in general lie with its trunk in the direction of flow. A tree thus trapped offers an area of :

$$\tfrac{1}{2}\left(\pi Db^2 / 4\right) = \pi / 8 Db^2 \qquad 5.5$$

to trap other debris. In general when (m-1) trees are trapped beneath a span the probability of an mth tree becoming trapped is:

$$PTm = \frac{\pi Db^2 / 8}{LsC - (m-1)(\pi Db^2 / 8)} \qquad 5.6$$

The probability of passing all NT trees from the watershed is:

$$(1\text{-PT1})^{NT} \qquad 5.7$$

The probability of at least one tree being trapped at a span is:

$$P1 = 1\text{-}(1\text{-PT1})^{N} \qquad 5.8$$

where N is the equivalent number of average trees arriving at the span. According to Li most trees will stay close to the bank, thus:

$$N = NT / 2 \qquad 5.9$$

So probability that m trees will be trapped is:

$$Pm = [1\text{-}(1\text{-PTm})^{[N-(m-1)]}]P(m\text{-}1) \qquad 5.10$$

On this basis the probability of a least m trees being trapped (for any m < N) can be estimated. In order to calculate Td and Dd it is necessary to estimate of the blockage area. It is assumed that debris elements stack up and that trees overlap by Db/2. Thus, for m trees trapped the percentage of the waterway area which is blocked is:

$$\%Blockage = \frac{m(\tfrac{1}{2}\pi\, Db^2/4)}{LsC} \times 100\% \qquad 5.11$$

Having estimated m and knowing Db, the increase depth of water (wd) at the bridge is assumed to be:

$$\Delta wd = \sqrt{mDd / 2} \qquad 5.12$$

The blockage generates a pressure force (Pf) which acts normal to the bridge is:

$$Pf = \tfrac{1}{2}\gamma . mDb^2 / 4 \qquad 5.13$$

where : γ is the specific weight of water.

5.12 Computer Model

A Bridge Pier scour with LWD computer program has been written in C++ (see Wallerstein and Thorne 1996) which calculates the probability of debris build-up at bridge piers and the

associated debris induced scour, based upon modified forms of the theoretical models published by Melville and Dongol (1992) and Simons and Li (1979).

The program runs the Simons and Li probability model and then calculates the potential pier scour due to a debris mat sized upon the blockage area, assuming all the trees available in the reach upstream become trapped beneath a span. This method therefore produces a very conservative factor of safety as it is unlikely that all the trees available upstream will become trapped. Initially, average (mid height) tree trunk diameter (Dt), a maximum tree diameter (Db), (either root ball or canopy, whichever is the larger), and average tree height (Ht) values are entered. Next, the number of trees approaching the bridge span (NT) is entered. Although Simons and Li suggest using N = NT/2 in the probability calculations, this model assumes that all the trees available in the upstream reach will pass through the span in question. However, the number of spans (S) between piers (P) that are set in the channel will normally be S = P+1 (counting the two spans between pier and river bank). It is therefore necessary, for an accurate assessment of blockage potential and debris related scour, to calculate probabilities for each span individually, perhaps using a simple division rule (N = NT / S) for N trees arriving at each span. It is left up to the user to make the appropriate adjustments for each span. NT can either be estimated in the field and entered as a total potential tree supply, or it can be estimated through calculation of the potential for bank retreat to supply debris from the upstream reach. To calculate the upstream supply an estimate of the riparian tree density is required, along with the length of the reach in question and the width of potential bank retreat width. The retreat width value can be determined using an appropriate bank stability model such as BURBANK (Burgi, 1995). The potential number of trees that will reach the span is then calculated as:

tree density x retreat width x reach length x 2 (two banks)

Finally, the bridge pier diameter (D), span between piers (ls) and average flow depth (Y) values are entered. Calculations then proceed as follows:

1) If tree height is less than the pier spacing the probability of the first tree becoming caught is calculated, followed by the probability of the next tree becoming caught consecutively. This is repeated for n trees up to N. In the calculation of trapping potential it is considered that, the use of the ratio of tree area to the entire area under the span as suggested by Simons and Li, is somewhat inappropriate as tree capture is dependent only upon the length of span and

diameter of tree given that the water level is constant. Deck elevation above the water (C) has therefore been substituted by maximum tree diameter (Db) in this model.

2) If tree height is greater than span width it is assumed, as outlined in the Simons and Li model, that at least one tree will become trapped and thus all subsequent trees arriving at the span will also be caught.

3) The percentage of the channel cross-sectional area that is blocked if all the trees supplied to the reach become trapped is calculated as outlined in the theoretical model for Ht < ls. However if Ht > ls Dt is substituted for Db and the blockage area is calculated as :

(((square root x blockage area) = blockage depth (assuming debris builds up as a square) x tree height) / (span width x flow depth)) x 100 %

This calculation assumes that, for Ht > ls, all trees will build up in a square formation, but at 90 degrees to the flow direction, as oppose to parallel with the flow when Ht < ls.

4) The hydrostatic pressure force (pf) on each pier per unit width is calculated as :

pf = bulk weight of water x blockage depth x 1 (unit width) x (blockage depth / 2).

5) Bridge pier scour with the debris accumulation is then calculated using the Melville and Dongol model. If Ht > ls the debris raft diameter is taken as the square root of the blockage area (assuming debris build-up is in a square). If Ht < ls debris raft diameter is assumed to be Ht because the debris is aligned parallel with the direction of flow. The scour depth is calculated using the base value of 2.4D and five additional multiplying factors. Factors which reduce the base value are applied where clear-water scour conditions exist (K_I), the flow depth is relatively shallow (K_y), and the sediment is relatively large (K_d). If piers are not cylindrical two additional factors are required; a shape factor (K_s) and an alignment factor (K_α). The program requires the following data to calculate these additional factors : mean approach velocity for the design flood (U); median particle size (d_{50}); the largest particle size (d_{max}); standard deviation of the particle distribution (σ_g) = d_{84}/d_{50}; pier diameter (D); angle of flow attack; pier dimensions; and pier shape. The user is also required to enter values for a threshold shear velocity (U_{*c}) and a threshold armouring shear velocity (U_{*ca}). U_{*c} and U_{*ca} are determined from a Shields chart of threshold conditions for sediment entrainment (see figure 1, Melville & Sutherland, 1988) using the sediment d_{50}, and the critical armouring grain size (d_{50a}) respectively. d_{50a} is calculated by the program and displayed on the screen, prior to the prompt for input of U_{*ca}. The alignment factor, K_α, must be determined by the user from a pier alignment factor graph (see figure 7, Melville & Sutherland, 1988).

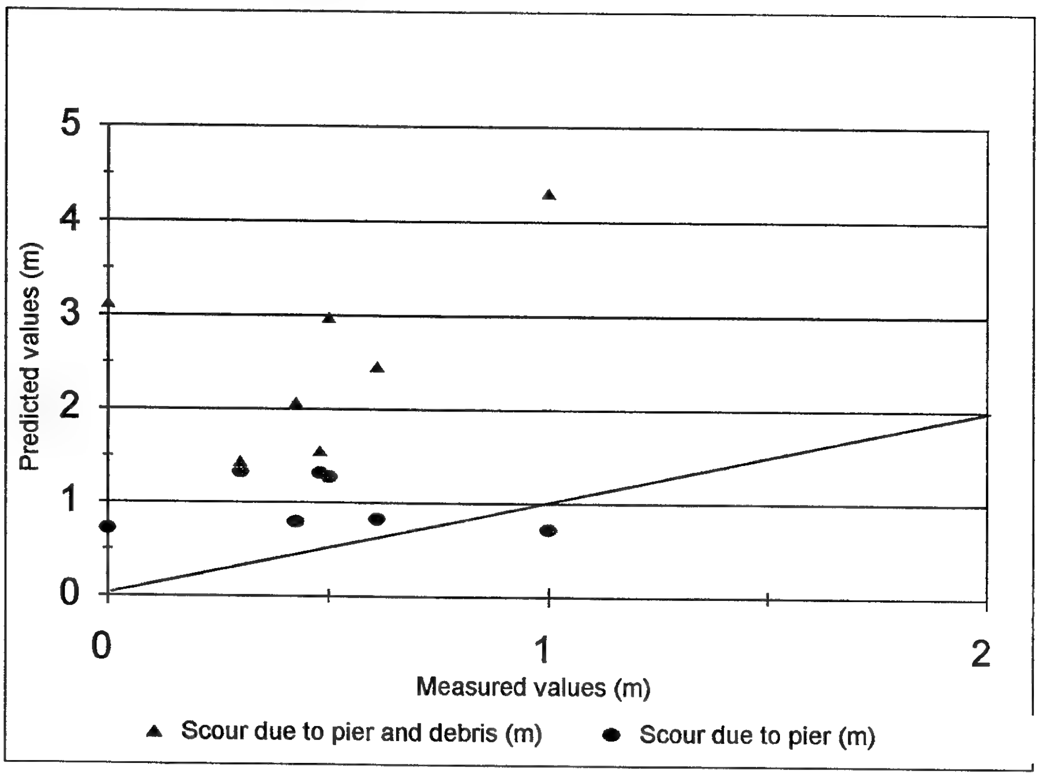
It should be noted that the formula, developed by Melville and Dongol for calculating debris related pier scour, was only developed for floating debris accumulations. However, it is considered by the authors that this formula can be extended to debris accumulations which have their base resting on the channel bed, as the critical factor in the calculation method is an effective pier diameter, which is, in any case, extended to the channel bed in the situation where the debris is floating.

The pier scour component of this model has been tested using field data collected from a number of bridges which span the survey reaches in northern Mississippi. Scour depths were measured at each site (during low flow conditions) on piers which had significant debris accumulations. The parameters required for the model calculations were also collected. However, bankfull discharge and channel dimension values, obtained from Watson et al. (1993) were used in the model both to simulate critical conditions and because accurate discharge measurements could not be made at the time of the survey. Logistical constraints also prevented the calculation of realistic upstream debris loadings that could arrive at each pier so these were substituted, by the dimensions of the debris accumulations already present at the time of survey. Figure 5.2a shows a summary table of the surveyed scour values and model results. Figure 5.2b shows a plot of these results. The diagonal line in this plot represents a perfect match between the actual measured scour depths and those predicted by the model. It is evident therefore that the model significantly overestimated scour due to both the pier and debris raft and slightly over estimates, except in one case, scour due to the pier alone. The predicted results would therefore appear to be rather conservative, although this does create a good factor of safety. The discrepancy between measured and predicted values is explained however by the fact that, scour hole depths are much greater under bankfull conditions, than those at low flow (when the measurements were made), but are subsequently reduced as flows recede, owing to the rapid deposition of the highly mobile sand and silt sediment load. In order to fully validate the model it will therefore be necessary to undertake further fieldwork to measure the various parameters required, including scour depth values during bankfull flow conditions. The model must also be validated using different channel environments such as armoured, gravel-bed rivers.

Figure 5.2a Pier scour summary table

creek	predicted pier scour	predicted pier & debris scour	actual scour
Abiaca 3	1.33	1.44	0.3
Harland 1	1.32	1.55	0.48
Abiaca 6	0.83	2.46	0.61
Fannegusha	0.72	3.12	0
Sykes	0.72	4.31	1
Redbanks	1.28	2.98	0.5
Burney Branch	0.80	2.07	0.425

Figure 5.2b Plot of predicted and measured pier scour depths



6 CONCLUSIONS

6.1 Geomorphological Impact of LWD

The following conclusions can be drawn from the results obtained in this study :

1) Sources of debris are site-specific rather than random and are usually associated with either meander migration or bed degradation leading to bank retreat.
2) The impact of debris jams in sand-bed rivers is different to that in gravel bed rivers in that distinct log steps do not form.
3) Debris is a key factor controlling channel bed topography in sand-bed rivers, creating a more heterogeneous profile than found in debris free reaches. This is important for creating productive aquatic habitat.
4) Debris jams in sand-bed rivers are stable in the short term (1 yr.). But total residence times may be longer in gravel-bed rivers.
5) Reconnaissance evidence suggests that jam forms change in a predictable manner downstream through the channel network as a function of key-debris mean height to channel width.
6) Debris jams dissipate flow energy and reduce sediment routing rates and therefore do not necessarily exacerbate bed degradation problems. The distribution of sedimentation and scour associated with debris jams appears have an geomorphically explainable distribution when related to drainage basin area.

6.2 Management Recommendations

The following management recommendations have been made based upon the findings of the study:

1) Basin-wide debris clearance is unnecessary and may have detrimental affects. Debris does not appear to exacerbate the degradation problems encountered in the bluff-line streams and can even accelerate aggradation processes locally.
2) Debris should be left in place or even introduced into the channel if the management aim is habitat enhancement.
3) Debris jams may have to be removed over the mid-range of basin sizes if the primary management aim is to reduce bank erosion
4) In rivers with run-of-river structures excessive debris loads may be partially reduced through control of upstream channel degradation and outer bank erosion at bends.

6.3 Debris Management for Run of River Structures

Debris build-up is a continual problem at locks, dams, bridges and water intakes and also causes disruption of water-based recreation activities. As a consequence debris control systems, which are often site specific, have been developed that incorporate various collection, removal and disposal elements. These systems are, inevitably, costly to construct and maintain. However, in order to develop a cost-effective debris control system at a new structure it would be beneficial to have some understanding of the debris dynamics within the relevant catchment area, upstream of that structure.

For example, McFadden and Stallion (1976) undertook a study for the Alaska District Corps of Engineers to determine the amount, source, and content of debris on the Chena River, and the magnitude of water levels which could cause a substantial debris movement. Also, of particular interest were the average size of the debris pieces and their potential for jamming or damaging the outlet structure of the Chena River Flood Control Dam which was being constructed at the time. These basin-wide studies helped them make more informed recommendations for counteracting log jamming in the dam gates. A system of debris-aligning pilings was advised with the spacing based upon maximum debris dimensions encountered on the river, and a back-up hoist with clam-shell bucket to remove logs that might manoeuvre into a jamming position. A cable boom system was rejected on the grounds that it was not as easy to clean as the gates themselves and presented a hazard to navigation. However, the number of projects that use watershed studies in this way is limited, and this is to the detriment of many structures. Martin (1989) concludes that, "while research studies have been undertaken to asses structural alternatives (to debris control) such as booms and "debris" basins (Perham, 1987) further research is needed in debris transport, particularly, quantifying the volume as it relates to distribution and time". In this regard it is recommended that more catchment-wide debris related studies are required to build up regional "Debris Budgets", in the same fashion as the calculation of channel sediment budgets. This would involve stream reconnaissance (Thorne 1993) to identify the location of major debris input zones and the flow/geotechnical input mechanisms, responsible for controlling the volume and timing of debris input; documentation of the composition and average dimensions of the debris load; monitoring and subsequent prediction of the return period of discharge events that can mobilize large quantities of debris; and, estimation of debris storage potential, in jams, bars, and in the channel and at any structures upstream of the structure in question. This information can be used to support estimates of the maximum potential volume of debris

likely to arrive at the structure in question for a given discharge event. Seasonal estimates of debris yields could then be used to produce an annual "debris hydrograph".

In the regions of the US visited under this project severe debris accumulation problems occasionally occur in reservoirs and in lock and dam operations. However the third author summarized that, "Little interest or incentive was perceived in elevating the state-of-the-art at the District level. Field personnel are open to new suggestions and/or procedures for managing debris, however, there will be resistance to implementation if there is an impact to their limited maintenance resources. It is evident that each District perceives debris management from a different perspective. Debris management received considerable attention in the south-central U. S., particularly where ice is not considered a major concern. However, debris management is a secondary concern compared to ice in the north and eastern U. S." Although the managers of individual structures cannot perhaps see the benefit of or afford measures suggested, run-of-river structures threatened by debris build-up would almost certainly benefit from debris monitoring studies and management strategies that were co-ordinated and funded at the District level. Watershed-wide debris studies and the synthesis of the information obtained would assist Districts in developing a predictive capability for floating debris dynamics. This, in turn, would allow the development of informed, pre-emptive debris control systems rather simply reacting to debris problems on an ad-hoc, site by site basis. The use of spatial analysis tool such as Geographical Information Systems (GIS) would undoubtedly facilitate the development of watershed debris monitoring and budgeting models.

In small watersheds it may be more cost effective to control debris at source by clearing trash and downed timber from the river floodplain, and through multipurpose channel stabilisation schemes (such as the Demonstration Erosion Control (DEC) project) which would help to reduce excessive debris input into the channel network through bank erosion or channel instability. However, it must be recognised that in-channel Large Woody Debris (LWD) is a beneficial and integral geomorphological and ecological component of the river system (see Wallerstein & Thorne, 1994 and 1995). Starvation of debris in low order streams could very well have undesirable negative environmental impacts and so the key to debris management must therefore be to moderate the debris budget and control debris output from high yield reaches upstream which feed debris into large rivers containing major structures. This can be achieved by holding debris back at natural debris jams and also by the creation of artificial

jams, in the form of retention structures similar to that developed and used in southern Germany (refer to section 5.1).

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